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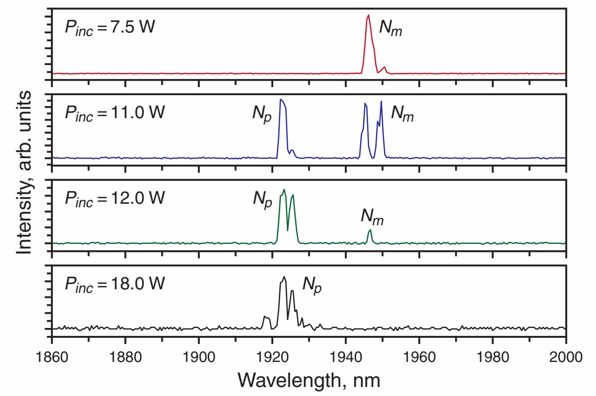
Abstract: We report on polarization switching in the $Tm:KLu(WO_4)_2$ laser between the N_m and N_p states oscillating at different wavelengths: 1946 nm for N_m and 1922 nm for N_p. There is a certain power range where the two laser polarizations coexist in this biaxial crystal. The switching strongly depends on the thermal management of the active medium through either the mode matching between the pump and the laser beams or the cooling of the crystal faces.



Evolution of the laser emission spectra below, in and above the region of polarization switching

Polarization switching in the 2-μm $Tm:KLu(WO_4)_2$ laser

M. Segura, [1] *M. Kadankov,* [2] *X. Mateos,* [1,3,*] *M.C. Pujol,* [1] *J.J. Carvajal,* [1] *M. Aguiló,* [1] *F. Díaz,* [1] *U. Griebner,* [3] *and V. Petrov* [3]

[1] Física i Cristallografía de Materials i Nanomaterials (FiCMA-FiCNA-EMaS), Universitat Rovira i Virgili (URV), Campus Sescelades c/Marcell Domingo, s/n, 43007 Tarragona, Spain
[2] Department of Quantum Electronics, Faculty of Physics, Sofia University, 5, James Bourchier Blvd., 1164 Sofia, Bulgaria
[3] Max-Born-Institute for Nonlinear Optics and Short Pulse Spectroscopy, 2A, Max-Born-Strasse, 12489 Berlin, Germany

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1. Introduction

The laser emission around 2 μm based on the $^3F_4 \rightarrow {}^3H_6$ transition of thulium (Tm^{3+}) is very interesting for applications in the field of medicine, mainly due to the strong optical absorption by water, and remote sensing (LIDAR) of CO_2 and water in the atmosphere, as well as for pumping optical parametric oscillators (OPOs) for conversion in the mid-IR with single [1] or dual-wavelength operation [2]. The laser operation with single doped Tm has been successfully demonstrated in a wide variety of hosts such as garnets (YAG) [3] and its isostructural $Lu_3Al_5O_{12}$ (LuAG) [4], fluorides ($LiYF_4$, $GdLiF_4$) [5,6], vanadates (YVO_4, $GdVO_4$) [7,8], and the double tungstates $KRE(WO_4)_2$ (shortly KREW with RE=Y, Gd, Lu) [9–11].

The monoclinic potassium double tungstate crystals doped with lanthanide ions, are established as promising solid-state laser materials providing very high laser efficiencies In particular, the $KLu(WO_4)_2$ (KLuW) crystal is very suitable as host for Yb and Tm ions [12]. The three orthogonal principal optical axes of this biaxial crystal are defined by the relation of the refractive indices $n_p < n_m < n_g$. The principal optical axis N_p is parallel to the b crystallographic direction, while N_m and N_g lie in the ac crystallographic plane. The principal optical axis N_g is at 18.5° clockwise with respect to c crystallographic direction when b is directed towards the observer [13].

* Corresponding author: e-mail: xavier.mateos@urv.cat

In this class of biaxial crystals, the absorption and emission bands are relatively broad and the transition cross-sections are very high for selected polarizations, make them also interesting for thin disk laser applications. In the case of Tm doping with a layer thickness of 80 μm, continuous-wave (CW) laser was achieved with 550 mW of maximum power [14]. For Tm:KLuW crystal at room-temperature, the absorption cross-section (σ_a) at 802 nm amounts to 5.95×10^{-20} cm^2 for $E\|N_m$, and 1.76×10^{-20} cm^2 for $E\|N_p$, and the emission cross-section (σ_e) at 1950 nm is 1.20×10^{-20} cm^2 for $E\|N_m$ and 0.57×10^{-20} cm^2 for $E\|N_p$ [11]. Selection rules in the electronic transitions for Tm ion (odd electrons number) in the C_2 symmetry are expected [15]. In the three-level Tm-laser system, these absorption and emission cross-section values, the gain cross-section σ_g, defined as $\sigma_g=\beta\sigma_e-(1-\beta)\sigma_a$, which depends on the inversion rate β and the pump reabsorption, change with temperature. It may happen that at a certain temperature the gain cross-section is similar for two polarizations at different wavelengths and simultaneous laser oscillation of two perpendicular polarizations at those wavelengths may occur.

Similar phenomenon was previously observed in some other laser crystals using Yb as the active ion, for example in the uniaxial vanadates as reported in [16–18] and the biaxial calcium oxiborates [19], in which an extensive theoretical work have been done concerning the anisotropy in the absorption and fluorescence taking into account the distribution of the polarization eigenmode vectors around the principal plane of the dielectric frame containing the optical singularities of the optical axes [20]. The anisotropic behavior of double tungstates can also be exploited such that the laser gains of two perpendicular polarizations have different spectral properties as in the work of A. Brenier [21] where a tunable dual-wavelength laser based in Yb:KGW was demonstrated oscillating at 1033–1046 nm range along N_p polarization and at 1020–1032 nm range polarized in the N_m-N_g principal plane. In some other works, the dual wavelength operation without polarization switching has been observed using Nd:YAG [22] in which the laser wavelengths correspond to the transitions between the Stark sublevels of the $^4F_{3/2}\rightarrow{}^4I_{11/2}$ transition of Nd, or Nd:YVO$_4$ and Nd:LuVO$_4$, in which the laser wavelengths correspond to the electronic transitions $^4F_{3/2}\rightarrow{}_4I_{11/2}$ and $_4F_{3/2}\rightarrow{}^4I_{13/2}$ [23–25]. Very recently, at 2-μm spectral range, simultaneous oscillation of two laser wavelengths in (Ho,Tm):KLuW system has been demonstrated [26], one generated from Tm ions tuned in the 1854 – 1980 nm range and the other from Ho ions tuned in the 1971 – 2063 nm range.

In this work, we report on switching between the two polarization states, N_m and N_p of the $^3F_4\rightarrow{}^3H_6$ transition of Tm, each of them with a characteristic wavelength, in a diode-pumped Tm:KLuW laser operating in CW regime. We are not aware of the existence of such polarization switching in other Tm-doped crystals.

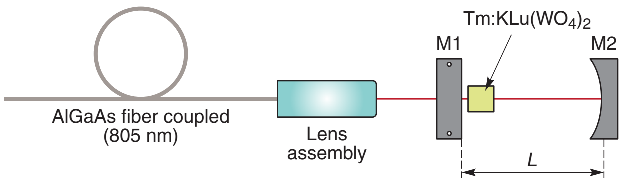

Figure 1 (online color at www.lphys.org) Experimental setup for the laser experiments

2. Laser experiments

For the laser experiments, the active elements were 3 at.% Tm:KLuW crystals grown by means of the top-seeded solution growth slow-cooling (TSSG-SC) method. The ion concentration measured by EPMA was 1.93×10^{20} at./cm^3. This doping level presented optimum laser performances in our previous work in CW regime with Ti:Sapphire and diode lasers pumping [11]. The crystals were cut for propagation along the N_g principal optical axis with 3 mm thickness and 1.5×3 mm^2 aperture along the N_p and N_m principal optical directions, respectively. The faces of the crystals normal to N_g were AR coated for the pump and laser wavelengths. The setup for laser experiments is shown in Fig. 1. A 200 μm core diameter (NA = 0.22) fiber-coupled AlGaAs laser diode emitting in the 805 – 807 nm range and delivering 20 W of maximum power was used as pump source. The pump beam was focused onto the crystal with a spot size of 200 μm through a special lens assembly with an imaging ratio 1:1. The two mirror cavity consisted of a flat input mirror (M1) with AR coating for the 770 – 1050 nm range and HR coating for the 1800 – 2075 nm range, and a concave output coupler (M2) with transmission (T_{oc}) of 1.5%, 3%, and 5% for 1820 – 2050 nm range and radii of curvature (R_{oc}) of 25, 50, and 75 mm to vary the mode matching of the pump and Tm-laser resulting in optimum cavity lengths of 24, 49, and 74 mm, respectively. The active element was placed very close to the input mirror at a distance of $\sim$1 mm. The active elements were cooled using two different Cu holders with circulating water at 16°C. The first one enabled contact with the two larger lateral surfaces of the crystal and the second one was in contact with all four lateral surfaces. Indium foil was used for better thermal contact between crystal and holder.

3. Results and discussion

Fig. 2a – Fig. 2c show the output power of the Tm laser against the incident pump power for three output couplers with different radii of curvature when only the two larger lateral surfaces of the active element are in contact with the crystal holder. At low pump powers and for all output couplers used in this experiment, the laser polarization that

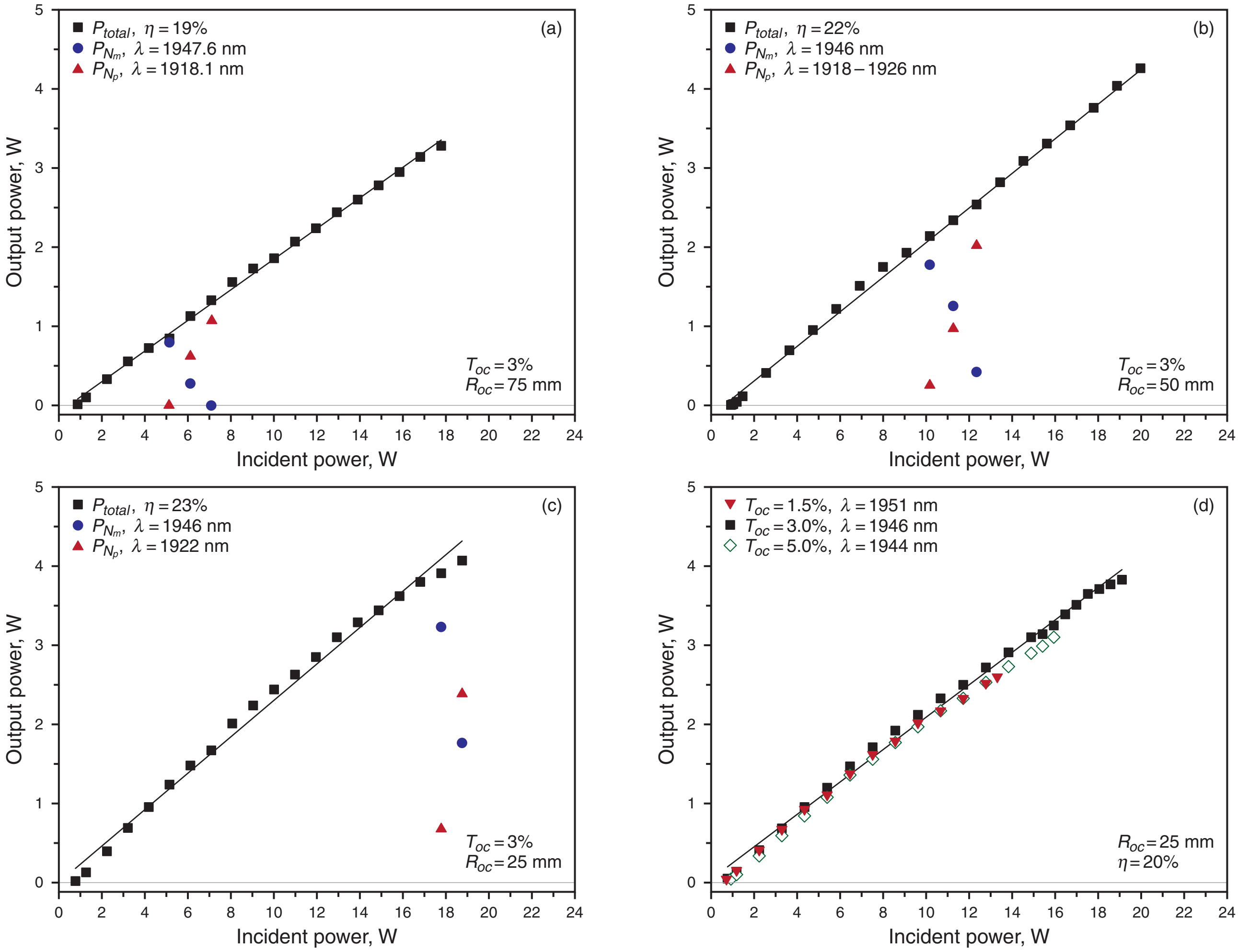

Figure 2 (online color at www.lphys.org) Polarization switching in the CW Tm:KLuW laser, cooling of two crystal surfaces (a) with $R_{oc} = 75$ mm, (b) $R_{oc} = 50$ mm output coupler, and (c) $R_{oc} = 25$ mm output coupler. (d) – cooling all four crystal surfaces and $R_{oc} = 25$ mm output coupler. The total output power in the coexistence region is the sum of the powers of both polarization states experimentally confirmed and η is the slope efficiency

naturally oscillates at threshold is that with $E \| N_m$ because of the larger gain cross-section compared to $E \| N_p$ [11].

In Fig. 2a, a $T_{oc} = 3\%$ and $R_{oc} = 75$ mm output coupler was used and the competition of two polarization states occurred in the 5–7 W range for the incident pump power. At an incident pump power of 5 W, the N_m polarized output of the Tm-laser, having reached less than 1 W, started decreasing (circles) while the N_p polarized component (triangles) appeared. This coexistence extended up to ~ 7 W of incident pump power. Above this power level, the N_p polarization dominated. Similarly, in Fig. 2b a $R_{oc} = 50$ mm output coupler with same transmission was used and the competition occurred in the $10-12$ W range for the incident pump power. In both cases, the total output power dependence remained linear as a function of the incident pump power.

In Fig. 2c, a $R_{oc} = 25$ mm output coupler was used, still cooling only the two larger faces of the crystal. In this case, mode matching was improved and competition of the two polarizations occurred at an output power level of 3.5 W (at much higher incident pump power ~ 18 W). The estimated values of the laser spot diameter for each R_{oc} mirrors are: 102, 124, and 140 μm for 25, 50, and 75 mm radius of curvature, respectively.

The above results can be compared with those obtained when cooling all four lateral surfaces of the crystal, which are shown in Fig. 2d for the same radius of curvature of the output coupler as in Fig. 2c). In this case, no competition of the two polarizations in the range of available incident pump power (up to ~ 20 W) was observed, independent of the output coupler transmission. In these conditions, the laser reached 4 W of output power operating at 1946 nm

	R_{oc}		
T_{oc}	25 mm	50 mm	75 mm
1.5%	No coexistence at 14.9 W $\lambda = 1952.5$ nm	$P_{coex} = 8.0$–10.7 W $\lambda_{N_m} = 1953.3$ nm $\lambda_{N_p} = 1946.7$ nm	$P_{coex} = 5.9$–7.0 W $\lambda_{N_m} = 1954.5$ nm $\lambda_{N_p} = 1947.2$ nm
3.0%	No coexistence at 14.9 W $\lambda = 1948.2$ nm	$P_{coex} = 8.5$–11.7 W $\lambda_{N_m} = 1946.0$ nm $\lambda_{N_p} = 1922.0$ nm	$P_{coex} = 6.4$–7.5 W $\lambda_{N_m} = 1947.2$ nm $\lambda_{N_p} = 1922.5$ nm
5.0%	No coexistence at 14.9 W $\lambda = 1945.7$ nm	$P_{coex} = 8.6$–11.7 W $\lambda_{N_m} = 1945.1$ nm $\lambda_{N_p} = 1912.6$ nm	$P_{coex} = 5.9$–7.5 W $\lambda_{N_m} = 1945.7$ nm $\lambda_{N_p} = 1913.2$ nm

Table 1 Polarization coexistence power range (P_{coex}) and laser wavelengths for N_m and N_p polarizations cooling the four faces of the crystals

($T_{oc} = 3\%$), linearly polarized along the N_m principal optical axis.

The effect of removing the coexistence region with the improved cooling of the crystals was pronounced in the case of $R_{oc} = 25$ mm mirror. In Table 1 the results obtained with several T_{oc}'s and R_{oc}'s are summarized cooling the four faces of the crystal. As can be seen, the coexistence range (in terms of incident power) is similar for different T_{oc}'s. The wavelengths for N_m and N_p polarizations remain nearly the same for different R_{oc} values but change to shorter values with increasing T_{oc} as typical for quasi-three level lasers. These laser wavelengths change with T_{oc} according to the gain curves.

Regarding the laser emission spectra, the behavior depending on the power level with the output coupler with $R_{oc} = 50$ mm, $T_{oc} = 3\%$ and four faces cooling is shown in Fig. 3. For low incident power (7.5 W) the wavelength oscillating with $E \| N_m$ is 1946 nm. In the coexistence region (11 W) where both polarizations have similar output powers (~ 1 W in Fig. 2b), the wavelength for N_p polarization is 1922 nm. At higher incident powers (12 W), N_m almost disappeared while N_p polarization dominated. Finally, near to the maximum available incident power, N_p is the only oscillating polarization. It means that the N_p polarization is more stable at higher powers with the resonator conditions already described.

Polarization switching effect is assigned to thermal load because when a mechanical chopper was used (duty cycle of 50%), polarization switches at yet higher incident power levels. In contrast to the works of J.H. Liu et al. [16–19], we did not observe any hysteresis in the coexistence region comparing the laser performance when the experiment was carried out increasing or decreasing the pump power.

To see the influence of the thermal effects in the active medium, we also used crystal cubes of $3 \times 3 \times 3$ mm^3 along N_p, N_m, and N_g. From these experiments, with four crys-

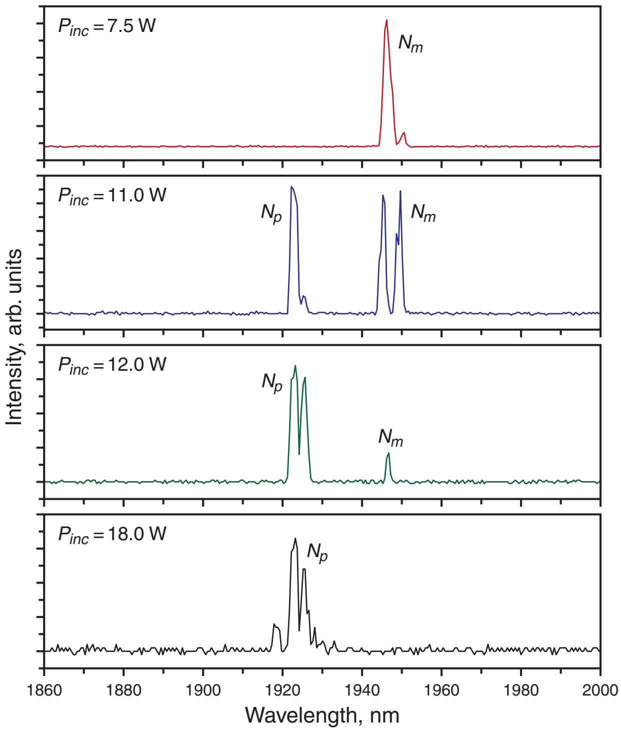

Figure 3 (online color at www.lphys.org) Evolution of the laser emission spectra below, in and above the region of polarization switching

tal faces in contact with the cooling holder, there is clear evidence that shorter crystal dimension along N_p helps significantly to reduce thermal loading allowing higher incident powers without damaging of the crystal but the polarization switching appeared around similar incident power ranges. Moreover, further reduction of the dimension along N_p (to 1 mm for example) led to strong thermal gradient between the axial region (high temperature) and the face in contact with the cooling holder (low temperature) which was detrimental for the beam quality, apparently affected by pronounced thermal lensing. This was confirmed by the necessity to increase the cavity length ~ 2 mm for each output coupler with $R_{oc} = 25$, 50, and 75 mm, from the initial ones at 24, 49, and 74 mm to 26, 51, and 76 mm, respectively, in order to achieve higher output powers. The polarization switching observed in the present work could also be suppressed by the insertion of an intracavity polarizer, however this would not prevent thermal loading, which in turn leads to thermal lensing or in the worse case crystal damage.

The temperature of the crystal increases with the pump power, making the re-absorption losses more pronounced. At 1950 nm, the re-absorption cross-section for N_m polarization is 0.11×10^{-20} cm^2 while for N_p it is 0.025×10^{-20} cm^2 [12]. At low pump levels the resulting gain cross-section is higher for N_m polarization, at a

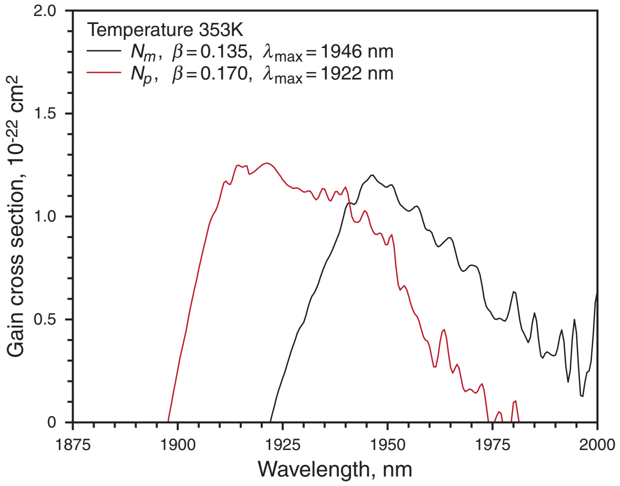

Figure 4 (online color at www.lphys.org) Gain cross-section, σ_g, of Tm:KLuW in the 1875 – 2000 nm range at 353 K for N_m and N_p

T, K	σ_g, N_m, 10^{-22} cm^2 at 1946 nm	σ_g, N_p, 10^{-22} cm^2 at 1922 nm
298	2.50, $\beta = 0.12$	1.26, $\beta = 0.15$
323	1.46, $\beta = 0.12$	1.41, $\beta = 0.12$
353	1.20, $\beta = 0.135$	1.25, $\beta = 0.17$
393	0.91, $\beta = 0.15$	0.88, $\beta = 0.18$
433	1.23, $\beta = 0.18$	0.88, $\beta = 0.20$

Table 2 Gain cross-section values calculated for $T = 298$, 323, 353, 393, and 433 K depending on the inversion ratios (β) for maximum gain

certain pump level and operating temperature of the crystal, the gain cross-sections of the N_m and N_p polarizations might become nearly equal at two different wavelengths, leading to competition between these two laser states. Since the absorption and emission cross-sections are different for the two polarizations, this can obviously happen only for different inversion rates β for the two polarizations at a fixed temperature, because the total gain always equals the non-saturable losses. Note, that above threshold, the inversion rate β in a three-level system depends not only on the pump parameters (intensity and cross-sections at the pump wavelength) but also on the laser intensity and the values of the cross-sections at the laser wavelength. The latter determine the inversion rate in unpumped regions, e.g. in the case of imperfect overlap. As a result, the laser output will consist of two components with perpendicular polarization states, $N_m - N_p$, emitting at different wavelengths.

To demonstrate the hypothesis exposed above for these two polarizations with gain maxima centered at 1946 nm for $E \| N_m$ and 1922 nm for $E \| N_p$ (laser wavelengths we achieved for each polarization) we measured the optical absorption and calculated the emission cross-section by the reciprocity method for several elevated temperatures. At those elevated temperatures the maximum of the gain curves for N_m shifted to longer wavelengths so that an appropriate inversion rate β made the maximum to be centered at 1946 nm. On the other hand, for N_p only a reduced number of inversion rate β values were valid to center the maximum of the gain curves at 1922 nm. In addition, to make the two gain curves equal with maxima centered at 1946 nm for N_m and 1922 nm for N_p, the only combination possible was such that the temperature is ~ 353 K. As shown in Fig. 4, at 353 K, N_m polarization exhibits maximum gain cross-section of $\sim 1.2 \times 10^{-22}$ cm^2 at 1946 nm for an inversion rate $\beta = 0.135$. At this temperature, N_p polarization exhibits already slightly higher maximum gain cross-section of $\sim 1.25 \times 10^{-22}$ cm^2 at 1922 nm for an inversion ratio $\beta = 0.170$. Some other values of gain cross-section (σ_g) and inversion ratios (β) are summarized in Table 2.

4. Conclusion

In summary, we observed and characterized polarization switching in the laser operation of a 3 at.% Tm:KLuW crystal. We established, that there is a competition of two polarizations, N_m and N_p oscillating at different wavelengths, and that this can be eliminated by modifying the design of the laser cavity and better cooling of the active medium. We also demonstrated that this polarization switching is mainly due to the change of the gain cross-section for each polarization with the temperature.

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